

EEG-Based Asynchronous BCI Controls Functional Electrical Stimulation in a Tetraplegic Patient

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The present study reports on the use of an EEG-based asynchronous (uncued, user-driven) brain-computer interface (BCI) for the control of functional electrical stimulation (FES). By the application of FES, noninvasive restoration of hand grasp function in a tetraplegic patient was achieved. The patient was able to induce bursts of beta oscillations by imagination of foot movement. These beta oscillations were recorded in a one EEG-channel configuration, bandpass filtered and squared. When this beta activity exceeded a predefined threshold, a trigger for the FES was generated. Whenever the trigger was detected, a subsequent switching of a grasp sequence composed of 4 phases occurred. The patient was able to grasp a glass with the paralyzed hand completely on his own without additional help or other technical aids.

Keywords and phrases: beta oscillations, motor imagery, functional electrical stimulation, brain-computer interface, spinal cord injury, neuroprosthesis.

1. INTRODUCTION

The idea of direct brain control of functional electrical stimulation (FES) seems to be a realistic concept for restoration of the hand grasp function in patients with a high spinal cord injury. Today, electrical brain activity either recorded from the intact scalp (EEG) or with subdural electrodes (ECoG) can be classified and transferred into signals for control of FES system (neuroprosthesis). Nowadays both implantable systems [1, 2] and devices using surface electrodes [3] are available for clinical use. For the transformation of mental commands reflected in changes of the brain signal into control signals for FES devices, an asynchronous, user-driven brain-computer interface (BCI) is necessary [4]. Such an asynchronous BCI analyses the EEG (ECoG) continuously and uses no cue stimuli.

For the realization of a reliable and easy to apply BCI, only one signal channel (one recording with two electrodes) should be used. Further, it is necessary to have a mental strategy established to produce short increases or bursts in the EEG (ECoG) amplitude and to detect the increase with a simple threshold comparator.

We report for the first time on restoration of hand grasp function composed of 4 phases by electrical stimulation of hand muscles with surface electrodes and control of the stimulation by one-channel EEG recording.

2. MATERIALS AND METHODS

2.1. Subject

The tetraplegic patient we report on is a 29-year old man suffering from a traumatic spinal cord injury since April 1998.

He is affected by a complete motor and sensory lesion below C5 and an incomplete lesion below C4. As a preparation for the experiment, the patient performed an individual stimulation program until he achieved a strong and fatigue resistant contraction of the paralyzed muscles of the hand and forearm. The residual volitional muscle activation of his left upper extremity is as follows.

Shoulder: active abduction and flexion up to 90°; grade 3/5 before - grade 4/5 after training, full rotational range of motion (ROM); full passive ROM.

Elbow: active flexion grade 3/5 before / grade 4/5 after training, no active extension (triceps grade 0/5); pro- and supination possible (partly trick movement); full passive ROM.

Forearm, hand, and fingers: M. extensor carpi radialis (ECR) showed a palpable active contraction (grade 1/5) without change over training; all other muscles grade 0/5; almost full passive ROM in finger joints; full wrist, thumb, and forearm ROM.

2.2. Functional electrical stimulation

Our aim was to find a functional grasp pattern that would bring the most benefit for our patient, and to find a practical way to generate it by use of surface stimulation electrodes. A kind of fine manipulating grasp, providing the ability to pick up objects from a table, for example, food or a glass, seemed to be most suitable. This grasp is generated by flexion in the metacarpophalangeal (MCP) joints of the extended fingers against the thumb, so that small objects are held between the ball of the end phalanx of the fingers and the thumb, while larger objects are held between the palmar side of the whole fingers and the thumb.

As a precondition for a functional hand grasp pattern, the wrist needs to be dorsal flexed and held stable in this position during flexion of the fingers. Due to the lack of an adequate active wrist extension and a partial denervation (lesion of peripheral nerve fibers) of the wrist extensor muscle (M. extensor carpi radialis muscle, grade 1/5) in our patient, it was not possible to get a stable dorsal flexion of the wrist by stimulation, forcing us to use a mechanical orthosis fixing the wrist in a dorsal flexed position.

An opening of the hand (phases 1 and 4, Figure 1) by extension of all fingers joints and the thumb could be achieved by stimulation of the finger extensors (M. extensor digitorum communis) and the thumb extensor muscle (M. extensor pollicis longus) with electrodes on the radial side of the proximal forearm.

For the actual grasping (phase 2, Figure 1), we simultaneously stimulated the finger flexors (M. flexor digitorum superficialis, less the M. flexor digitorum profundus) by one pair of electrodes on the ulnar side of the proximal forearm and the intrinsic hand muscles with two further electrodes on the dorsal side of the hand. The application of the orthosis for dorsal flexion of the wrist leads to a light flexed position of the thumb sufficient for serving as a stable counterpart to the flexing fingers. Therefore, no additional stabilization of the thumb via surface stimulation was necessary.

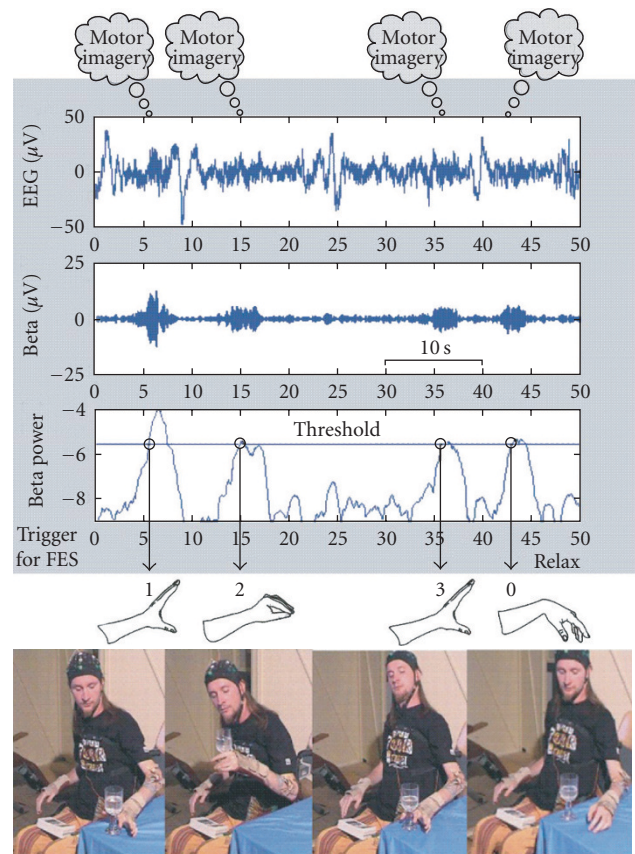


FIGURE 1: Example of bipolar EEG recording from the vertex (upper trace) bandpass filtered (15–19 Hz) EEG signal (middle) and band power time course (lower trace, arbitrary units) over a time interval of 50 seconds. Threshold and trigger pulse generation after FES operation and grasp phases are indicated. Shots of the grasping are shown in the lower part.

For the external stimulation, we used a stimulator (Microstim8, Krauth & Timmermann, Germany) with biphasic, rectangular constant current pulses. The stimulation frequency was set to 18 Hz; the current was set for each pair of electrodes on an individual level. Due to the integrated microcontroller, we were able to implement different stimulation patterns for a grasp sequence directly into the device.

The output of the BCI was then used as a trigger signal for switching between the different grasp phases (phase 0 - no stimulation, phase 1 - opening hand, phase 2 - grasping, phase 3 - releasing, phase 4 = phase 0, see Figure 1).

2.3. EEG recording and processing

The EEG was recorded bipolarly from 2 gold-electrodes fixed in a distance of 5 cm in an anterior-posterior position on the vertex (Cz according to the international 10–20 system). The EEG signal was amplified (sensitivity was 50 μV) between 0.5 and 30 Hz with a bipolar EEG-amplifier (Raich, Graz) and sampled with 128 Hz. The signal was online processed by bandpass filtering (15–19 Hz), squaring, averaging over 128 samples, and logarithmizing. After passing a threshold de-

tector, a trigger pulse was generated followed by a refractory period of 3 seconds. The threshold was empirically selected by comparing the band power values obtained from resting and imagery periods.

2.4. Mental strategy

Our patient participated in a number of BCI training sessions with the goal of developing a mental strategy to induce movement-specific EEG patterns and to transform these patterns into a binary control signal. During the training, several types of imaginations were used in order to increase the classification accuracy. Imaginations of left versus right hand movements were carried out first. Then single-foot motor imageries versus relaxing or hand movement imagination could increase the accuracy. Finally, after 55 training sessions, best results were achieved by the imagination of both feet versus right hand imagery. These two patterns were discriminable online 100%.

3. RESULTS

As a first result of the BCI training, the patient was able to control the opening and closing of an electromechanical hand orthosis by 2-channel EEG recording [5]. Inspection of EEG patterns induced by motor imagery has shown that hand motor imagery was accompanied by a weak EEG desynchronization [6] whereas foot motor imagery induced large bursts of beta oscillations with frequencies of 17 Hz. It is therefore quite logical to use only one mental state, namely, the state inducing beta oscillations for control purposes. At the end of the training, the patient has learned to voluntarily induce beta bursts. An example of an EEG signal recorded bipolarly on the vertex close to the foot representation area is shown in Figure 1. The EEG signal is disturbed by large artifacts from eye movements, because the patient watched his hand. Bandpass filtering of the EEG in the beta band (15–19 Hz) reveals 4 bursts of beta activity with a duration of about five seconds within the 50 seconds of recording period. The beta power increase was used for generation of a trigger pulse, whenever power exceeded the predefined threshold. Applying a refractory period of 3 seconds a maximum of 20 switches can theoretically be achieved per minute.

The use of only 2 electrodes placed close to the vertex and the recording of one bipolar EEG channel minimizes the effects brought about by using muscle activity for control. Calculating the power spectra and computing the power in the 20–60 Hz band (part of the EMG activity band) showed a band power close to zero.

The patient was able to trigger the FES grasp phases by the induction of beta burst on his own. Using this setting, our patient was able, for the first time after the accident, to drink from a glass without any help and without the use of a straw.

4. DISCUSSION

It is interesting to note that the motor imagery induced beta burst is a relative stable phenomenon in our patient with a constant frequency around 17 Hz. Since this time about 3

years ago, foot motor imagery was always able to induce beta bursts with constant frequency components. The generation network of these beta bursts is very likely in the foot representation area and/or the supplementary motor area (SMA). In a foot motor imagery task, both primary sensorimotor area and SMA play an important role, whereby the SMA is located in the medial portion of Brodman's area 6 in front of the foot representation area. From scalp recordings, we cannot expect, however, to differentiate between both sources, because of the proximity of SMA and foot representation area [7].

There is strong evidence from EEG, MEG, and ECoG recordings that different motor tasks including imagery can generate beta oscillations between 20–35 Hz in the SMA and/or the foot representation area of able-bodied subjects [8, 9, 10, 11, 12]. Common for all these reports on induced beta oscillations close to the vertex are its strict localization to the midcentral area and its dominant frequency between 20–35 Hz.

There is, however, one important difference between all the observed beta oscillations associated with a motor task in able-bodied subjects and the induced beta oscillations in our tetraplegic patient: The former are generated after termination of the motor task, the latter during execution of the motor task. Whether in both cases the same or similar networks in the SMA and/or foot representation area are involved needs further research. Important is that the beta oscillations on the vertex induced by the reported patient are a robust and reliable phenomenon that can be generated at "will".

For an EEG-based control of a neuroprosthesis in all-day life under real-world conditions, the performance of the BCI has to be maximized by using a minimum number of electrodes. Using more than one single bipolar derivation, it is likely to help identifying more than a binary switch concluding in the realization of a more complex EEG-based control for the future.

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REFERENCES

- [1] B. Fromm, R. Rupp, and H. J. Gerner, "The freehand system: an implantable neuroprosthesis for functional electrostimulation of the upper extremity," *Handchirurgie, Mikrochirurgie, Plastische Chirurgie*, vol. 33, no. 3, pp. 149–152, 2001.
- [2] P. H. Peckham, M. W. Keith, K. L. Kilgore, et al., "Efficacy of an implanted neuroprosthesis for restoring hand grasp in tetraplegia: A multicenter study," *Archives of Physical Medicine and Rehabilitation*, vol. 82, no. 10, pp. 1380–1388, 2001.
- [3] M. R. Popovic, D. B. Popovic, and T. Keller, "Neuroprostheses for grasping," *Neurological Research*, vol. 24, no. 5, pp. 443–452, 2002.
- [4] G. Pfurtscheller and C. Neuper, "Motor imagery and direct

- brain-computer communication," *Proc. IEEE*, vol. 89, no. 7, pp. 1123–1134, 2001.
- [5] G. Pfurtscheller, C. Guger, G. R. Müller, G. Krausz, and C. Neuper, "Brain oscillations control hand orthosis in a tetraplegic," *Neuroscience Letters*, vol. 292, no. 3, pp. 211–214, 2000.
- [6] G. Pfurtscheller and F. H. Lopes da Silva, "Event-related EEG/MEG synchronization and desynchronization: basic principles," *Clinical Neurophysiology*, vol. 110, no. 11, pp. 1842–1857, 1999.
- [7] A. Ikeda, H. O. Lüders, R. C. Burgess, and H. Shibasaki, "Movement-related potentials recorded from supplementary motor area and primary motor area. Role of supplementary motor area in voluntary movements," *Brain*, vol. 115, no. 4, pp. 1017–1043, 1992.
- [8] C. Neuper and G. Pfurtscheller, "Motor imagery and ERD," in *Event-Related Desynchronization. Handbook of Electroenceph. and Clin. Neurophysiol. Revised Edition*, G. Pfurtscheller and F. H. Lopes da Silva, Eds., vol. 6, pp. 303–325, Elsevier, Amsterdam, the Netherlands, 1999.
- [9] G. Pfurtscheller, M. Woertz, G. Supp, and F. H. Lopes da Silva, "Early onset of post-movement beta electroencephalogram synchronization in the supplementary motor area during self-paced finger movement in man," *Neuroscience Letters*, vol. 339, no. 2, pp. 111–114, 2003.
- [10] S. Ohara, A. Ikeda, T. Kunieda, et al., "Movement-related change of electrocorticographic activity in human supplementary motor area proper," *Brain*, vol. 123, no. 6, pp. 1203–1215, 2000.
- [11] J. Kaiser, W. Lutzenberger, H. Preissl, D. Mosshammer, and N. Birbaumer, "Statistical probability mapping reveals high-frequency magnetoencephalographic activity in supplementary motor area during self-paced finger movements," *Neuroscience Letters*, vol. 283, no. 1, pp. 81–84, 2000.
- [12] R. Salmelin, M. Hämäläinen, M. Kajola, and R. Hari, "Functional segregation of movement-related rhythmic activity in the human brain," *NeuroImage*, vol. 2, no. 4, pp. 237–243, 1995.

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